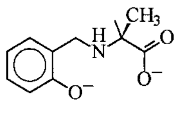
Thermal Conversion of a Helical Coil into a Three-Dimensional Chiral Framework**

John D. Ranford,* Jagadese J. Vittal,* Daqing Wu, and Xiandong Yang

The quest to rationally design solids by the emerging principles of crystal engineering is continuing at an accelerating pace.[1] The ultimate goal for the crystal engineers is to synthesize three-dimensional structures with desired properties for practical applications. In the newly emerging area of crystal engineering, several metal-organic compounds have been used successfully in the construction of novel architectures that are unprecedented in naturally occurring solids.[2] We are currently interested in the synthesis of 3D open frameworks with large chiral cavities; these solids with chiral channels have potential applications, for example, in the separation of enantiomers and the purification of drugs. Such chiral coordination polymer architectures can in principle be generated by the self-assembly of chiral or achiral building blocks. Zaworotko and co-workers have recently described the formation of chiral architectures from achiral molecular components.[3] We have reported the structures of two 3D frameworks, one held together by hydrogen bonding and the other by covalent bonding, formed from a Zn^{II} complex containing a chiral ligand.[4] The covalently bonded network has also been obtained by the topochemical dehydration of the hydrogen-bonded network assisted by N-H $\cdots$ O hydrogen bonds.

Self-assembly of supramolecules with helical structures by simple mixing of ligands and metal ions has been one of the focuses in supermolecular chemistry.[5] In most cases self-assembly of metal ions and multidentate ligands resulted in the formation of covalently bonded single-, double-, triple-, and even quadruple-stranded metal helicates.[5, 6] However, it appears that the use of helical metal-organic polymers as building blocks for the formation of 3D networks has not been explored before.[7] Here we report the preparation of a novel, single-stranded helical coordination polymer containing Cu^{II} from simple, chiral amino acid derivatives. These helical polymers are aligned parallel in the solid state. On heating, the single-stranded helices lose water molecules and cross-link to produce a chiral open framework. This demonstrates for the first time the conversion of 1D helical strands into a chiral framework structure. This thermal transformation is accompanied by dehydration and appears to be assisted by N-H $\cdots$ O hydrogen bonding.

Most metal ions, when presented with tridentate ligands, will preferentially bind two of the chelating units to form an octahedral moiety. However, the coordination sphere around Cu^{II} is distorted and unless the ligand is unusually flexible, copper(II) will bind only one ligand. The remaining coordination site(s) are occupied by solvent, anions, or bridging ligands. We have employed the latter to prepare phenolato-bridged, dimeric copper(II) complexes of *N*-(2-hydroxybenzyl)-L-alanine (H$_2$sala). This ligand with Cu^{II} gives control over the axial coordination donors. Addition of cupric acetate to H$_2$sala affords a polymer of dimers, [{[Cu(sala)]$_2$(H$_2$O)}$_n$] (**1**), as characterized by single-crystal X-ray diffraction (Figure 1).[8]



sala

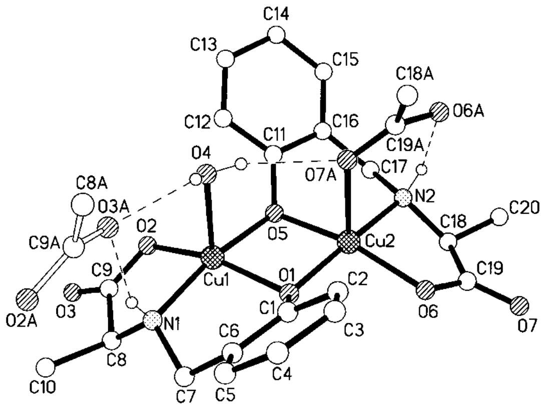


Figure 1. A perspective view showing the geometry of the dinuclear **1**, numbering scheme, and the hydrogen-bonding contacts. The hydrogen atoms attached to carbon atoms were omitted for clarity. Selected fragments of neighboring molecules involved in hydrogen bonding are shown with open bonds. Selected bond distances [Å] and angles [°]: Cu1 $\cdots$ Cu2 2.9496(6), Cu1–O1 1.975(3), Cu1–O2 1.928(3), Cu1–O4 2.288(4), Cu1–N1 1.984(4), Cu2–O1 1.936(3), Cu2–O5 1.977(3), Cu2–O6 1.958(3), Cu2–N2 1.984(3), Cu2–O7a 2.258(3), C9–O2 1.274(5), C9–O3 1.227(5), C19–O6 1.282(5), C19–O7 1.237(5); Cu1-O1-Cu2 97.9(1), Cu1-O5-Cu2 96.7(1), O1-Cu1-O5 82.1(1), O1-Cu2-O5 82.9(1), O1-Cu1-N1 93.8(1), O5-Cu2-N2 94.5(1), O2-C9-O3 123.8(5), O6-C19-O7 124.2(4).

The ligands coordinate in the plane of the square-pyramidal Cu^{II} centers through phenolato and carboxylato O atoms and the secondary amine N atom to give a phenolato-bridged dimer. The two apical coordination sites are occupied by either water or carboxylato bridges, and it is control of these sites that determines the supramolecular architecture. Coordination of the amine N atom creates a new chiral center, which means the sala ligand, when complexed, is a diastereomer, with the hydrogen atoms on the secondary amine and Cα adopting a *trans* arrangement about the C–N bond axis due to steric interactions.[9] One axial site in the dimer is occupied by a water molecule (site B), and the other (site A) forms a bridge to an adjacent dimer through a carboxylato O atom (Figure 1). The net result is a helical polymer formed from apically linked dimers.[10] The helical strands are further sustained by O-H $\cdots$ O and N-H $\cdots$ O hydrogen bonding (Figure 2).[11] The water molecule and the carboxylate ligand attached to the Cu^{II} centers are on the same side, supported by H-O-H $\cdots$ O-C hydrogen bonding. Further, the NH hydrogen atom of the ligand from site A forms a hydrogen bond to the C=O oxygen atom of the bridging carboxylate group. This

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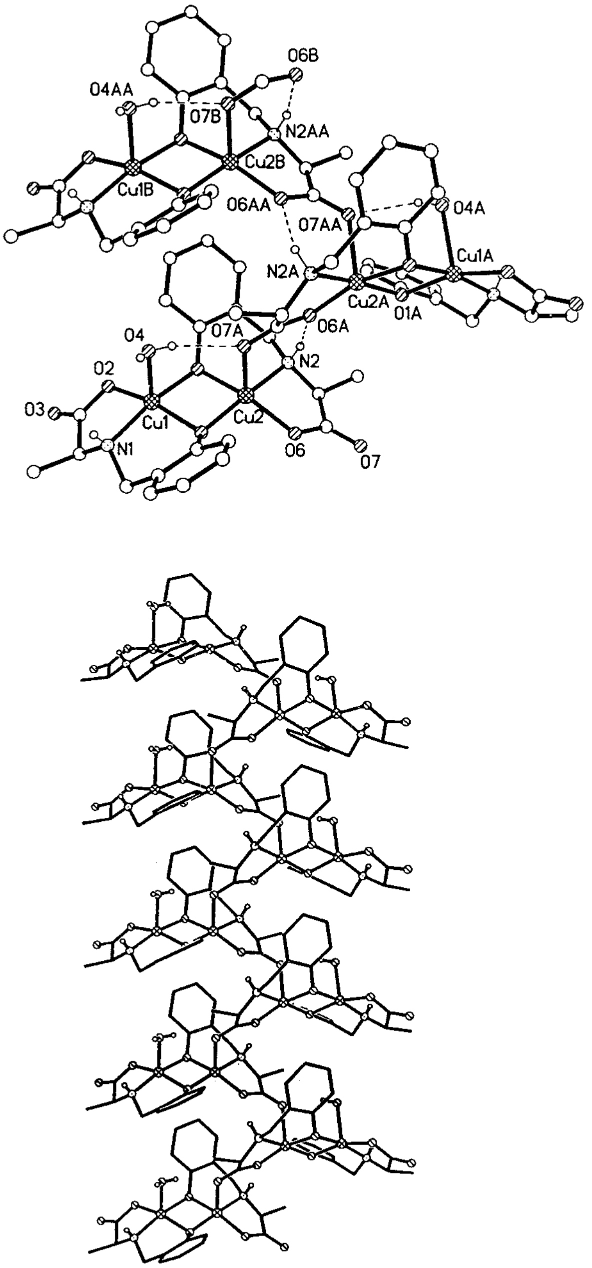


Figure 2. Top: The hydrogen-bonded pattern within the helical coordination polymer **1**. Bottom: A section of the helical coil of **1** along the *a* axis.

covalently bonded helical coordination polymer, sustained by the hydrogen bonds from the backbone of the ligands, is reminiscent of peptide α-helices.[12]

The helical strands are arranged parallel to the *a* axis and are further hydrogen bonded to one another in the *bc* planes (Figure 3). The carbonyl oxygen atom of the ligand from site B is further intermolecularly hydrogen bonded to two hydrogen atoms, N–H and O–H. As a result, chiral channels are created along the *a* axis with approximate dimensions 4 × 9 Å (based on the non-hydrogen contacts). The view shown in Figure 3 is similar to the honey-combed hydrogen-bonded chiral network that we have reported for $[\{Zn(sala)(H_2O)\}_2] \cdot 2H_2O$ (**2**).[4a] The channels in **1** are very narrow when compared to those in **2**, and they can still accommodate small guest molecules like water. The geometric proximity of the carboxylate groups and the Cu^{II} atoms of the B sites appears to be favorable for topochemical reactions to occur. The short Cu···O distance (3.70 Å) is maintained by the hydrogen-bonded network in the *bc* planes. When the water molecule on site A is removed, this carboxylate ligand is expected to bond to the copper due to this topochemical geometry.

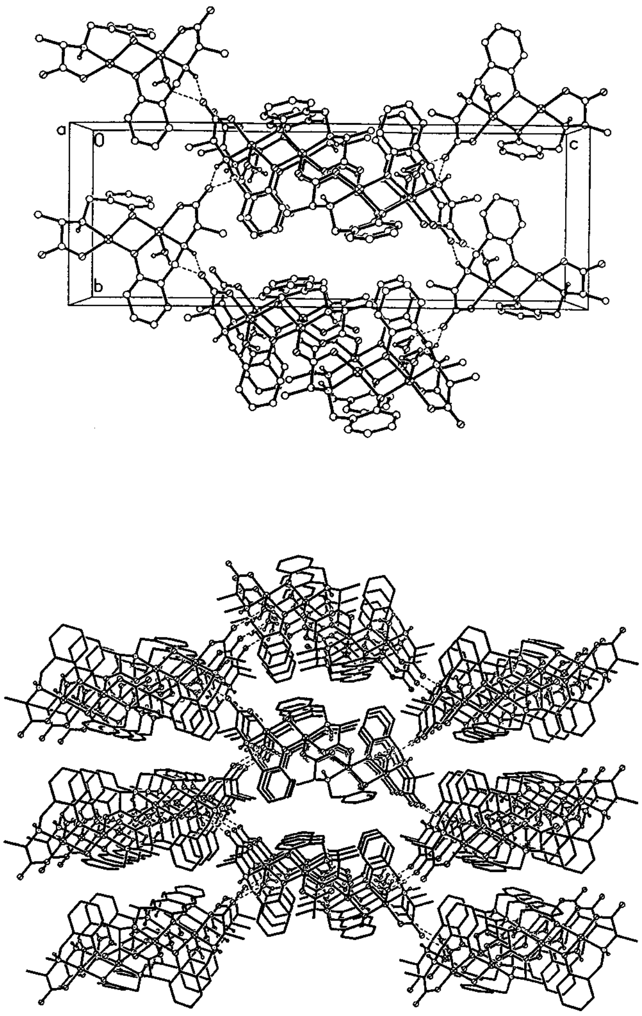
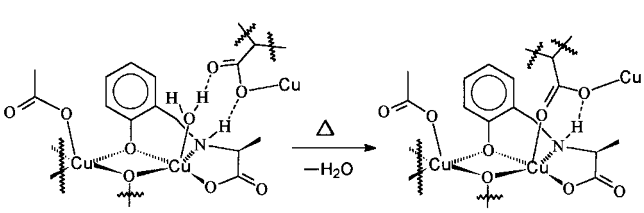


Figure 3. Top: Unit cell showing the hydrogen-bonding network in **1** in the *bc* plane. Bottom: View of **1** down the *a* axis, illustrating the channels resulting in a 3D network coordination polymer.

As anticipated, removal of the water molecule in **1** by thermal dehydration[13] yields anhydrous $[\{Cu(sala)\}_n]$ (**3**; Scheme 1), where the basic dimeric structure has remained intact but now a porous, 3D network coordination polymer has been established. The X-ray structure analysis[14] of **3** (Figure 4) reveals this architecture is isomorphous and



Scheme 1. Schematic drawings of the coordination environments and hydrogen bonding in hydrated **1** (left) and dehydrated **3** (right), illustrating the change from hydrogen bonding to covalent bonding.

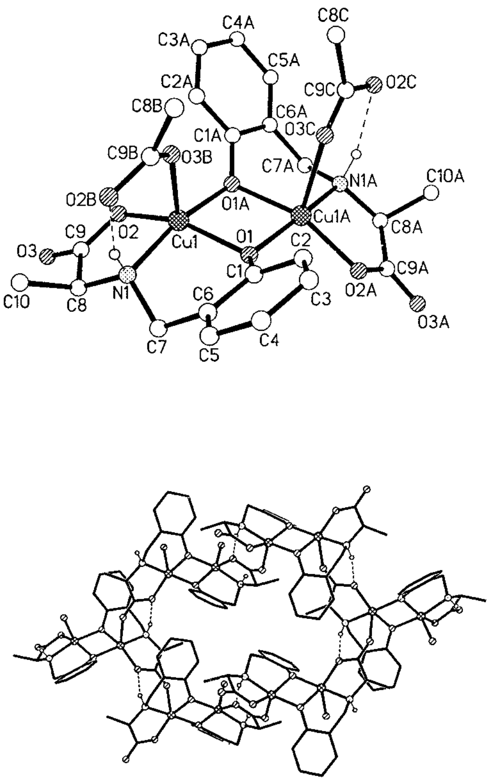


Figure 4. Top: A perspective view of **3** showing the numbering scheme, the coordination geometry around copper atoms, and the hydrogen-bonding contacts. Selected bond distances [Å] and angles [°]: Cu1 ⋯ Cu1A 3.0310(5), Cu1–O1 1.948(1), Cu1–O2 1.951(1), Cu1–N1 1.986(2), Cu1–O3B 2.341(2), C9–O2 1.290(2), C9–O3 1.237(2); Cu1-O1-Cu1A 101.02(6), O1-Cu1-O1A 78.97(6), O1-Cu1-N1 94.03(6), O2-C9-O3 124.5(2). Bottom: A segment of the three-dimensional network of **3** illustrating the close resemblance to **1**.

isostructural with the analogous Zn^{II} complex [{Zn(sala)}$_n$] (**4**).[4a] The arrangement of dimeric units in the solid-state structure of **3** is very similar to that of **1** as well as of **4**. The formation of **3** is accompanied by the loss of hydrogen bonds to the water molecule. However, the N-H ⋯ O hydrogen bond is preserved,[15] as in **4**. Although minimum movement of atoms and conformational changes are enough to obtain the structure of **3** from **1**, the conversion is accompanied by a change in the crystal system and space group. Also, the single crystal of **1** became powdery when heated to 100 °C. Attempts to rehydrate **3** to give **1** have been unsuccessful, and this process appears to be irreversible, as expected. The chiral channels in **3** are just a bit smaller than those observed in **4**. However, the rehydration experiments did not yield any product that accommodates guest water molecules in these voids.

We summarize the results and implications as follows:

1) This is the first example for the use of a helical coordination polymer as the building block to produce a 3D coordination framework with chiral channels.
2) This is the second example of a solid-state conversion of one type of network into another by thermal dehydration. The presence of complementary hydrogen bonds is strategic in these transformations.
3) The dihydrated dimer complex [{Cu(sala)(H_2O)}$_2$], analogous to [{Zn(sala)(H_2O)}$_2$] has not been isolated. Although the monohydrate Zn complex analogue of **1** is not known, during dehydration one would expect that the dihydrated Zn complex would go through a monohydrated intermediate similar to **1**. However, in the case of [{Zn(sala)(H_2O)}$_2$] the thermal dehydration appears to take place in a single step (as indicated by differential thermal analysis (DTA)).[4a]
4) In the Zn system, the covalent bonded network **4** was obtained from another similar hydrogen-bonded framework, **2**. In the work presented here, the same chiral network (but with Cu atoms) **3** was synthesized from different helical building blocks, **1**. This appears to be the first example of a true "solid-state supramolecular synthesis" or "crystal synthesis", as coined by Desiraju,[16] of an inorganic system by two different synthetic routes.

Experimental Section

H_2sala was synthesized by a procedure entirely analogous to that in ref. [9] for other ligands.

1: H_2sala (195 mg, 1.00 mmol) and LiOH (24 mg, 1.00 mmol) were stirred in water (10 mL) for 30 min, and then the reaction mixture was filtered. To the filtrate was added a solution of Cu(CH_3CO_2)$_2$ · H_2O (200 mg, 1.00 mmol) in water (10 mL). Dark green crystals formed in a few minutes, and were separated by decantation and dried in air. Yield: 196 mg (74 %). Elemental analysis calcd for $C_{20}H_{24}Cu_2N_2O_7$: C 45.2, H 4.6, N 5.3; found: C 45.0, H 4.7, N 5.2; IR (KBr): $\tilde{\nu}$ = 1624 (s, $\nu_{as}(CO_2)$), 1483 (s, $\nu_s(CO_2)$), 1275 cm^{-1} (s, ν(C=O)).

3: Compound **1** (200 mg, 0.75 mmol) was heated to 115 °C for 2 h to remove all water. The anhydrous material was recrystallized from water to give crystals suitable for X-ray structure analysis. Yield: 93 mg (48 %). Elemental analysis calcd for $C_{20}H_{22}Cu_2N_2O_6$: C 46.8, H 4.3, N 5.5; found: C 46.8, H 4.4, N 5.3; IR (KBr): $\tilde{\nu}$ = 1609 (s, $\nu_{as}(CO_2)$), 1477 (s, $\nu_s(CO_2)$), 1288 cm^{-1} (s, ν(=O)). The product also forms from the filtrate of **1**. Both preparative methods suggest that **3** is the thermodynamic product of this reaction.

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[8] a) Crystal structure determination of $[\{[Cu(sala)]_2(H_2O)\}_n]$ (**1**). Orthorhombic, space group $P2_12_12_1$, $a = 7.3850(2)$, $b = 10.0669(2)$, $c = 28.6676(8)$ Å, $V = 2131.27(9)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.65$ g cm^{-3}. All hydrogen atoms were located successfully. The positional and common isotropic thermal parameters were refined for the hydrogen atoms in the coordinated water molecule, and riding models were used for the remaining hydrogen atoms. In the final least-squares refinement cycles on $|F|^2$, the model converged at $R_1 = 0.0505$, $wR_2 = 0.0694$, and GOF = 1.039 for 3483 reflections with $F_o > 4\sigma(F_o)$ and 288 parameters, and at $R_1 = 0.1004$ and $wR_2 = 0.0820$ for all 5262 data. The Flack parameter x was refined to $-0.01(2)$. b) General crystallographic details: Data were collected on a Siemens SMART CCD system with graphite-monochromated $Mo_{K\alpha}$ radiation using a sealed tube (2.4 kW) at 23 °C. Absorption corrections were made with the program SADABS (G. M. Sheldrick, Göttingen, **1996**), and the crystallographic software package SHELXTL (SHELXTL Reference Manual, Version 5.03, Wisconsin, **1996**) was used for all calculations. Crystallographic data (excluding structure factors) for the structures reported in this paper have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication nos. CCDC-133087 (**1**) and -133088 (**3**). Copies of the data can be obtained free of charge on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: (+44)1223-336-033; e-mail: deposit@ccdc.cam.ac.uk).

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[10] Analogous Cu^{II} single-crystal X-ray structures for helices with the ligands *N*-(2-hydroxybenzyl)-L-tyrosine, *N*-(2-hydroxybenzyl)glycine, and H_2sala have also been solved. For the latter the compound is the enantiomer of **1**: J. D. Ranford, W. T. Robinson, J. O. Svensson, J. J. Vittal, D. Wu, X. Yang, unpublished results.

[11] Close intermolecular hydrogen-bonding contacts between two [Å] and three centers [°]: $H2\cdots O6^{i}$ 2.01(4), $H4A\cdots O7^{i}$ 2.19(3), $H1\cdots O3^{ii}$ 2.27(4), $H4B\cdots O3^{ii}$ 2.10(5), $N2\cdots O6^{i}$ 2.903(5), $O4\cdots O7^{i}$ 2.898(4), $N1\cdots O3^{ii}$ 2.98(6), $O4\cdots O3^{ii}$ 2.655(4); N2-H2-O6^{i} 161(3), O4-H4A-O7^{i} 161(6), N1-H1-O3^{ii} 156(4), O4-H4B-O3^{ii} 143(5); the N1–H1, N2–H2, O4–H4A, and O4–H4B distances are 0.75(4), 0.93(4), 0.74(3), and 0.74(3) Å, respectively. The H4A-O4-H4B angle is 100(6)°. Operators for generating equivalent atoms: i: $x + ½, -y + ½, -z + 1$; ii: $-x + 1, y + ½, z + ½$.

[12] See, for example, H. Lodish, D. Baltimore, A. Berk, S. L. Zipursky, P. Matsudaira, J. Darnell, *Molecular Cell Biology*, 3rd ed., Scientific American Books, New York, **1996**.

[13] Thermogravimetric analysis of **1** indicated a weight loss of 3.7 % in the temperature range 70–90 °C, corresponding to the loss of one molecule of water per dimer (expected weight loss 3.4 %) and the formation of the anhydrous compound **3**. The X-ray powder pattern of this anhydrous material was the same as that of **3**. Species **1** and **3** show the same decomposition pattern, which starts at about 240 °C. The structures of the bulk materials for **1** and **3** were confirmed by matching their X-ray powder patterns with those generated from the corresponding singles. Compound **3** was also prepared independently. The crystal structure was carried out on the single crystal grown during the synthesis (see the Experimental Section).

[14] Crystal structure determination of $[\{Cu(sala)\}_n]$ (**3**): Tetragonal, space group $P4_32_12$, $a = 8.8790(1)$, $c = 24.9879(2)$ Å, $V = 1969.96(4)$ Å^3, $Z = 4$, $\rho_{calcd} = 1.731$ g cm^{-3}. All hydrogen atoms were located successfully, and riding models were used. In the final least-squares refinement cycles on $|F|^2$, the model converged at $R_1 = 0.0226$, $wR_2 = 0.0517$, and GOF = 1.00 for 2371 reflections with $F_o > 4\sigma(F_o)$ and 137 parameters, and at $R_1 = 0.0257$ and $wR_2 = 0.0529$ for all 2526 data. The Flack parameter x was refined to $-0.016(13)$.[8b]

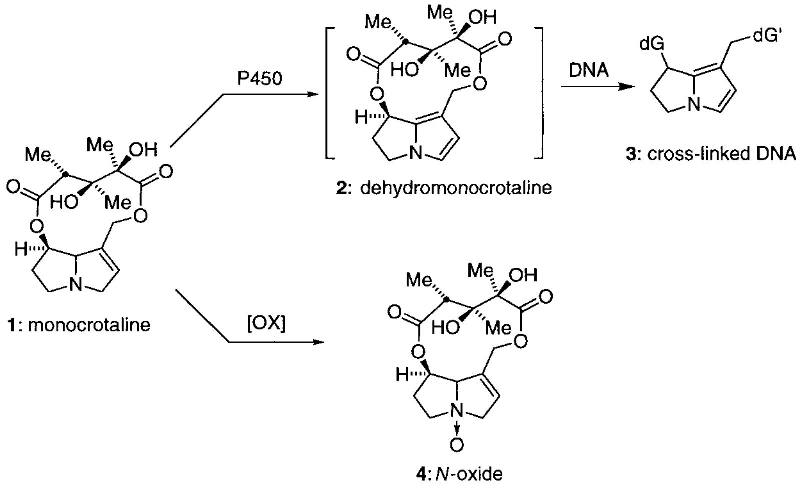
[15] Hydrogen-bonding parameters: $H1\cdots O2^{i}$ 2.03(2) Å, $N1\cdots O2^{i}$ 2.93(2) Å, and N1-H1$\cdots$O2^{i} 164(2)°. Operator for generating equivalent atoms: i: $x + 0.5, -y + 0.5, -z + 0.25$.

[16] G. R. Desiraju, *Angew. Chem.* **1995**, *107*, 2541–2558; *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 2311–2327.

Reductive Activation of a Hydroxylamine Hemiacetal Derivative of Dehydromonocrotaline: The First Reductively Activated Pyrrolizidine Alkaloid Capable of Cross-Linking DNA[**]

Jetze J. Tepe and Robert M. Williams[*]

Pyrrolizidine alkaloids (PAs), such as monocrotaline (**1**, Scheme 1), are potent hepatotoxins and carcinogens isolated from a wide variety of plants.[1, 2] Owing to their geographical



Scheme 1. Pyrrolizidine alkaloid monocrotaline (**1**) and derivatives **2**–**4**.

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